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Discussion on "Seismic displacement along a log-spiral failure surface with crack using rock Hoek–Brown failure criterion"

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ABSTRACT

This discussion is based on the paper by Zhao et al. [4] (hereafter identified as "the authors" or "the original paper"). In the original paper, the authors presented a numerical model to calculate the seismic displacement for rock slopes with cracks using the Hoek-Brown yield criterion. For the proposed numerical model, the upper bound limit analysis and rigid block displacement technique were employed in which the actual horizontal and vertical earthquake ground motion records were utilized in the analyses. This discussion addresses the theoretical issues of the computed permanent seismic displacements in conjunction with the upper bound limit analysis using the rigid block displacement technique. In addition, the discussion comments on some issues related to the assumption of using the factor of safety being less than 1 for a calculation of induced seismic displacement under an actual time history of horizontal and vertical accelerations, and the use of fixed crack depth ratios of 0.1 and 0.2 in the parametric studies of the original paper.

1. Discussion

The kinematic approach of the upper bound (UB) limit analysis (LA) is based on the plastic bound theorem [1], and provides a powerful framework for analyzing stability problems in geotechnical engineering [2,3]. The UBLA assumes a perfectly plastic material and the associated flow rule, and its framework is illustrated in Fig. 1. According to the UB theorem [1], UBLA is involved with a calculation of a kinematically admissible velocity field that satisfies velocity boundary conditions, compatibility equation, and associated flow rule. Then, the upper bound limit load on the exact collapse load can be obtained by invoking the principle of virtual work that equates the power expended by the external loads to the power dissipated internally by plastic deformation. As shown in Fig. 2, the equation of virtual work deals with two separate and unrelated fields, namely an equilibrium stress field and a compatible displacement field, that are brought together, side by side but independently, in the equation. The inequality sign associated with the principle of virtual work (see Fig. 1) indicates the upper bound solution on the exact solution, and can be mathematically proved by using the convexity of a yield surface and the associated flow rule [2,3].

The authors [4] presented an interesting research topic of the pseudo-static approach [5–7] that employed UBLA for analyzing seismic slope stability and seismic displacement of a rock slope with a crack. The rock was assumed to obey the generalized Hoek-Brown (GHB) failure criterion [8], while a log-spiral failure surface was employed in the UB analysis. Newmark's sliding block concept [9] in conjunction with the numerical UB log-spiral model with the rigid block displacement technique was described and applied to compute permanent seismic displacements of rock slopes with cracks as well as the factor of safety of rock slopes considering actual horizontal and vertical earthquake ground motion records. In order to model GHB criterion for UB rigid block mechanism, the external tangent method [10–12] was adopted in the original paper [4] to determine a tangent linear Mohr-Coulomb failure envelope with the tangential properties, namely instantaneous cohesion and frictional angle, that was assumed to be externally tangent to the GHB nonlinear criterion. This method applied to GHB was called as H-B criterion in the original paper [4] in which the optimal location of tangency point of the externally tangent linear Mohr-Coulomb failure envelope and the critical location of rotational body center of rock slope were determined in the UB optimization method. In addition, the equivalent Mohr-Coulomb (M-C) criterion fitted with an average linear relationship to the GHB nonlinear curve for a range of minor principal stress [8] was also employed so as to compare the difference in the safety factor and seismic displacement between H-B and M-C criteria. By employing the actual horizontal and vertical earthquake ground motions of the Imperial Valley and

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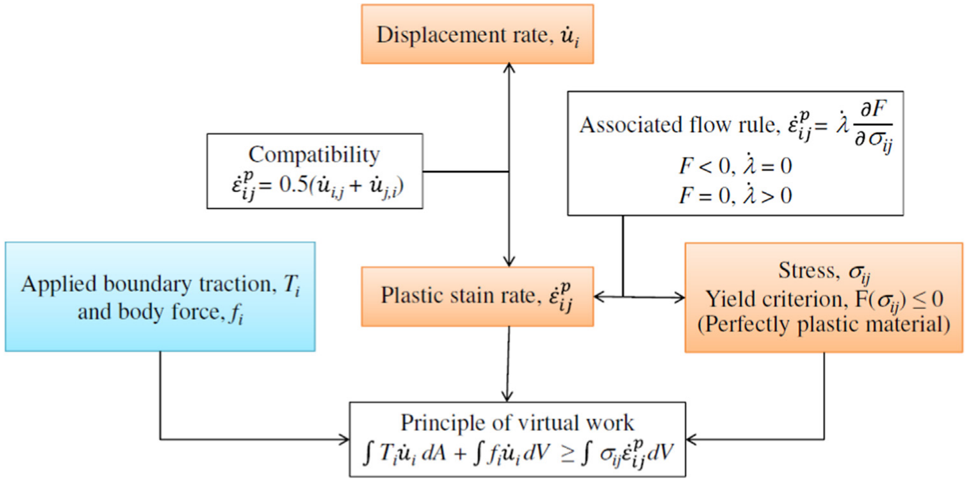

Fig. 1. Framework of upper bound limit analysis of the classical plasticity theory.

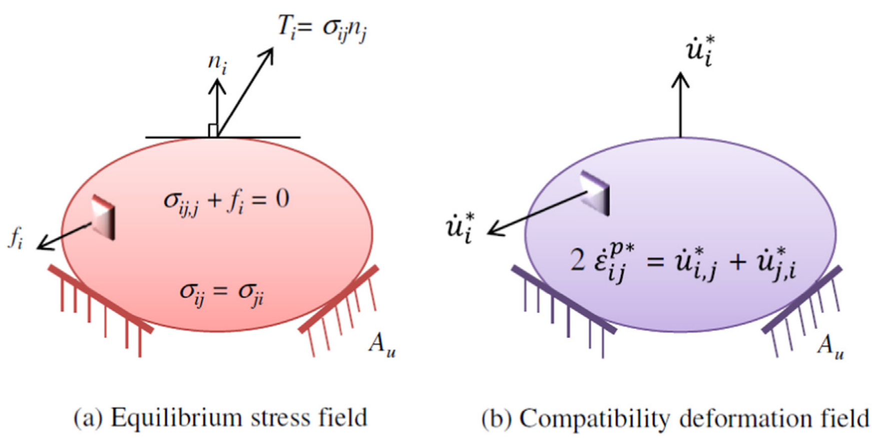

Fig. 2. Two independent sets in the principle of virtual work.

Northridge earthquake records, various parametric studies including crack depths, HB material parameters, H-B and M-C were examined. Several interesting and important findings were reported by the authors, namely the overestimation of stability assessments (i.e., both safety factors and permanent seismic displacements) of rock slopes using M-C criterion, and the importance degree of H-B parameters (i.e., *GSI*, m_i, *D* and σ_{ci}) to the stability assessments, and the significance influence of crack depths on the permanent seismic displacement with the H-B criterion.

In this discussion of the original paper [4], the discussers focus on the following issues: 1) the rigorousness of induced permanent seismic displacement; 2) the assumption of the use of the factor of safety being less than 1 for the calculation requirement of permanent seismic displacement; and 3) fixed crack depth ratios of 0.1 and 0.2 used in the parametric studies of Figs. 8–12 in the original paper [4].

The first issue of the discussion pertains to the rigorousness of a solution of permanent seismic displacement presented in the original paper [4]. In practice, a calculation of a permanent seismic displacement of a slope is conventionally performed using the sliding block method originally proposed by Newmark [9], and has been advocated by many researchers [13–19]. In this method, when an applied horizontal acceleration record is above the level of the yield horizontal acceleration, the permanent seismic displacement is assumed to be calculated from an application of Newton's second law of motion that determines an acceleration of the sliding rock mass. Accordingly, the permanent seismic displacement is obtained by double integrating the acceleration of motion equation over time interval. Considering actual horizontal and vertical earthquake ground motion records, the authors extended this concept for a rock slope with a crack using the UB log-spiral failure surface. For the log-spiral failure mechanism, the concept of rotational acceleration of rotating rock mass is employed instead of the sliding acceleration. The discussers agree well with the authors' model such that the UB log-spiral failure surface provides a more critical failure mechanism than the traditional sliding mechanism of Newmark [9]. In addition, the discussers believe and advocate that Newmark's sliding block concept [9] in conjunction with the pseudo-static approach [5–7] is a convenient and effective framework for the calculation of permanent seismic displacement of slopes. However, "computed seismic displacement" reported in the original article [4] should be interpreted as the approximate solution since Newmark's method with the pseudo-static approach cannot satisfy the general requirements for a solution of dynamic boundary value problem in continuum mechanics [e.g., 20–22], as shown in Fig. 3. For the theoretical point of view, Newmark's method [9] with the pseudo-static approach [5–7] does not consider the rigorous equations in the continuum level of rock mass, namely dynamic equilibrium equation, compatibility equation, applied stress and displacement boundary conditions, and a suitable constitutive law of rock mass. The latter is the key of an accurate and realistic prediction of seismic displacement of rock slope, and is capable of describing the cyclic and rate dependent behavior of rock accurately [e.g., 23–27]. Thus, in addition to being an approximate solution, "seismic displacement" obtained from the original paper [4] should be considered as a practical indication that provides useful information for a problem that is likely to be susceptible to a seismic risk potential. When a large permanent seismic displacement of rock slope is computed from the original paper, the rigorous approach of